NEW COSMOLOGICAL STRUCTURES ON MEDIUM ANGULAR SCALES DETECTED WITH THE TENERIFE EXPERIMENTS

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ABSTRACT

We present observations at 10 and 15 GHz taken with the Tenerife experiments in a band of the sky at Dec.=+35°. These experiments are sensitive to multipoles in the range $l = 10 - 30$. The sensitivity per beam is 56 and 20 μK for the 10 and the 15 GHz data, respectively. After subtraction of the prediction of known radio-sources, the analysis of the data at 15 GHz at high Galactic latitude shows the presence of a signal with amplitude $\Delta T_{\rm RMS} \sim 32$ μK. In the case of a Harrison-Zeldovich spectrum for the primordial fluctuations, a likelihood analysis shows that this signal corresponds to a quadrupole amplitude $Q_{\rm RMS-PS} = 20.1^{+7.1}_{-5.4}$ μK, in agreement with our previous results at Dec.+=40° and with the results of the COBE DMR. There is clear evidence for the presence of individual features in the RA range 190° to 250° with a peak to peak amplitude of $\sim$110 μK. A preliminary comparison between our results and COBE DMR predictions for the Tenerife experiments clearly indicates the presence of individual features common to both. The constancy in amplitude over such a large range in frequency ($10 - 90$ GHz) is strongly indicative of an intrinsic cosmological origin for these structures.

Subject headings: cosmology - large scale structure of the universe - cosmic microwave background

1. INTRODUCTION

The study of the cosmic microwave backround (CMB) has produced crucial advances in cosmology in recent years with the statistical detection of the fluctuations by the COBE DMR instrument (Smoot *et al.* 1992; Bennett *et al.* 1996), the direct observation of CMB features on scales $\gtrsim 5^\circ$ (Hancock *et al.* 1994) and the detections of signals on smaller angular scales down to a few arcminutes (see Hancock *et al.* 1997*a* for a summary of the present observational status). Current observations permit the determination of the overall level of normalization and constrain the CMB power spectrum on multipoles up to $l \sim 700$ thereby providing good evidence for the existence of the Doppler peak predicted by standard inflationary scenarios (Hancock *et al.* 1997*a*). Potentially, the power spectrum of the CMB fluctuations will allow the cosmological parameters (the curvature of the Universe, the baryonic content, the Hubble constant, etc) to be determined to an uncertainty of a few per cent. Additionally, the possible existence of a foreground of gravitational waves (Crittenden *et al.* 1993; Steinhardt 1994) can be determined from measurements of the CMB power spectrum on angular scales $\gtrsim 2^\circ$ ($l \lesssim 30$). To achieve these goals, more sensitive observations are needed over a wide range of angular scales and covering larger regions of the sky; observations over a range of frequencies are required to identify and remove Galactic foregrounds. The results presented here correspond to scales 2-10° and therefore can help to establish the overall level of normalization and test for the presence of gravitational waves. In the following, a description of the instrumental set-up and the observations (Section 2) is followed by an analysis of the data including a joint-likelihood analysis with the previous results of our experiment at an adjacent declination (Section 3). Our conclusions are given in Section 4.

2. OBSERVATIONS

The Tenerife CMB experiments have been extensively described in previous papers (see for instance Davies *et al.* 1996). Basically the suite of instruments consists of three radiometers, each with two independent channels, operating at frequencies of 10, 15, and 33 GHz. The instruments use a double-differencing technique where one of the resultant three 5° beams lies on the meridian and the other two (negative and half the amplitude of the central beam) are separated by $\sim 8^\circ$ in right ascension. Each day the instruments scan a band of the sky at constant declination. Observations are repeated over many days in order to achieve the sensitivity levels necessary to observe CMB anisotropies. Data processing includes the removal of points taken in poor atmospheric conditions, or corresponding to times when technical

failures in the instrumental system have occurred. Also all data taken closer than 50° to the Sun or 30° to the Moon are removed. The remaining data are dominated by low-order baseline variations which differ from day to day and have an atmospheric origin (Davies *et al.* 1992, 1996). The angular scales of such variations are larger than the beam response of the instrument and are removed by a maximum entropy method (Jones *et al.* 1997). Results published up to now include observations at 10, 15, and 33 GHz in a single strip at Dec.=+40° (Watson *et al.* 1992; Hancock *et al.* 1994) along with data at several declinations ranging from +35° to +45° at 10 GHz and from 37.5° to 42.5° at 15 GHz (Gutiérrez *et al.* 1995).

The data presented here cover a band of the sky at Dec.=+35° and were taken in several observing campaigns between 1988 March and 1996 April at 10 GHz, and between 1992 March and 1995 March at 15 GHz. In the region of the scan at high Galactic latitude the number of independent observations contributing to each 1° bin in RA is between 50 and 110 at 10 GHz, and between 60 and 160 at 15 GHz depending on the RA, with more observations at higher RA. The mean sensitivities in a beam-sized region (5°×5°) are 56 and 20 μK at 10 and 15 GHz, respectively. This represents an improvement by more than a factor of 2 with respect to the previous results (Gutiérrez *et al.* 1995) at 10 GHz. Figure 1 shows the stacked results in the region RA=160° − 250° corresponding to Galactic latitudes $b \gtrsim 40°$. Data are shown binned in a 4° interval in RA and therefore a single structure on the sky is sampled with at least 6 points across the triple-beam response. The maximum excursion at both frequencies is ~ 100 μK. The sensitivity of the data at 15 GHz is sufficiently high to show clear structures in the range RA=190°−250°. The statistical amplitude of the signals is quantified in the following sections.

3. ANALYSIS

3.1. The Foregrounds

We have concentrated our analysis on the region RA=161° − 250°, which is at Galactic latitude $b \gtrsim 40°$. In this section we consider the possible sources of non-CMB foregrounds in our data. The contribution from known point sources has been calculated using the Kuhr *et al.* (1981) catalogue and the Green Bank sky survey (Condon, Broderick & Seielstad 1989) complemented by the Michigan and Metsahovi monitoring programme. In the Dec.=+35° band of the sky the most intense radio-source at high Galactic latitude is 1611+34 (RA=$16^{\mathrm{h}}11^{\mathrm{m}}48^{\mathrm{s}}$, Dec.=$34°20'20''$) with a flux density ~ 2 Jy at both 10 and 15 GHz. After convolution with the triple beam of our experiment this source gives peak amplitudes of ~ 60 and $\sim$30 μK at 10 and 15 GHz, respectively, which are at the limit of detection of each data set. The rms point source

contributions along the Dec.=+35° scan are 26 and 11 μK at 10 and 15 GHz, respectively. These values agree closely with 27 and 12 μK at 10 and 15 GHz read directly from the plots of Franceschini *et al.* (1989) for a beamwidth of 5°. The agreement is not surprising since the main contribution to the point-source background is from sources stronger than 0.1 Jy, all of which are included in the Green Bank survey. Point sources are therefore only responsible for a small fraction of the detected signals. In the following analysis we have subtracted this point-source contribution.

In previous papers (Davies, Watson & Gutiérrez 1996), we have demonstrated the unreliability of the high-frequency predictions of the diffuse Galactic foreground using the low-frequency surveys at 408 MHz (Haslam *et al.* 1982) and 1420 MHz (Reich & Reich 1988) and have emphasized the necessity of using observations at higher frequencies. It is possible to estimate the magnitude of such a contribution from a comparison between our own measurements at 10 and 15 GHz and the COBE DMR results at 31, 53, and 90 GHz. In Sections 3.2 and 3.3 it will be shown how the Galactic foreground can contribute only with a small fraction to the signal detected at 15 GHz.

3.2. Estimates of the CMB Fluctuation Level

Figure 2 presents the auto-correlation of the 15-GHz data in the region at RA=161° − 250°. The error-bars were determined by standard Monte Carlo techniques. These techniques were also used to obtain the confidence bands in the case of pure uncorrelated noise (long-dashed lines) and the expected correlation (short-dashed line) in the case of a Harrison-Zeldovich spectrum for the primordial fluctuations with an amplitude corresponding to the signal of maximum likelihood (see next paragraph). Clearly the Harrison-Zeldovich model gives an adequate description of the observed correlation and shows that the results are incompatible with pure uncorrelated noise. The cross-correlation between the data at 10 and 15 GHz is inconclusive as it is dominated by the noisy character of the 10-GHz data.

We have applied a likelihood analysis described in detail by Hancock *et al.* (1994) to the data at 10 and 15 GHz in the range RA=161° − 250°. Assuming a Harrison-Zeldovich spectrum for the primordial fluctuations, the likelihood curve for the 15-GHz data shows a clear peak (5.5×10^4 normalized respect to the value for zero signal) at a rms temperature fluctuation in the data $\Delta T_{\rm RMS} \sim 32$ μK. Analyzing the curve in a *Bayesian* sense with uniform prior we obtained $\Delta T_{\rm RMS} = 32^{+11}_{-9}$ μK, which corresponds to an expected power-spectrum normalization with a quadrupole amplitude $Q_{\rm RMS-PS} = 20.1^{+7.1}_{-5.4}$ μK (68% confidence level). These results do not depend strongly on the precise region analyzed; for instance analyzing the

sections RA=161° − 230° or RA=181° − 250°, we obtain $Q_{\rm RMS-PS} = 19.0^{+9.0}_{-6.5}$ μK and $Q_{\rm RMS-PS} = 20.0^{+8.0}_{-6.0}$ μK, respectively. By using Monte Carlo techniques (5000 simulations) we have demonstrated that, for our data, the maximum likelihood estimator is essentially unbiased. As a consequence of the noise level in the 10-GHz data, there is no evidence of signal in the likelihood analysis of the data at this frequency. However, we obtained a limit on $Q_{\rm RMS-PS} \leq 33.8$ μK (95% C.L.), which is compatible with the amplitude of the signal detected at 15 GHz. The signal at 15 GHz ($Q_{\rm RMS-PS} = 20.1$ μK) is compatible with the signal $Q_{\rm RMS-PS} = 18$ μK present in the COBE DMR data (Bennett *et al.* 1996) also estimated on the Harrison-Zeldovich model. However, assuming that COBE DMR data give the correct normalization for the cosmological signal, our slightly higher normalization may be a signature of some small galactic contamination in the data at 15-GHz.

We have run a joint likelihood analysis (Gutiérrez *et al.* 1995) between the 15-GHz data presented here and those at Dec.=40° presented in Hancock *et al.* (1994) taking into account the small corrections due to the presence of atmospheric correlated noise between channels (Davies *et al.* 1996). The angular separation between the strips is equal to the half-power beamwidth of the individual antennas and corresponds to an overlap of ∼ 30% of the beam areas. As a consequence the scans at Dec.=+35° and Dec.=+40° are largely independent. We have chosen the region between RA=161° − 230° at Dec.=+40° and thus excluded the variable radio source 3C 345 (RA∼ 250°) that was clearly detected in our data. The combined data set was used to obtain quadrupole amplitude for different assumed values of the spectral index n ($P(k) \propto k^n$). Figure 3 shows the amplitude of the signal for each model and the one-sigma level bounds in the spectral index versus $Q_{\rm RMS-PS}$ plane. The relation between the expected quadrupole and the spectral index in such tilted models can be parameterized by $Q_{\rm RMS-PS} = 25.8^{+8.0}_{-6.5} \exp\{-(n-0.81)\}$ μK. In the case of a flat spectrum ($n = 1$) we obtain $Q_{\rm RMS-PS} = 21.0^{+6.5}_{-5.5}$ μK, in agreement with the results obtained analyzing independently the strips at Dec.=+35° (see above) and Dec.=+40° ($Q_{\rm RMS-PS} = 22^{+10}_{-6}$ μK, Hancock *et al.* 1997*b*). Our data can not be used on their own to constrain effectively the spectral index n, but we have already established limits on n from a comparison of our Dec.=+40° data and the COBE DMR results (see the discussion in Hancock *et al.* 1997*b*). A refinement of these estimates by including the Dec.=+35° data will be discussed in a forthcoming paper.

3.3. Comparison with Features in the COBE DMR Data

A first direct comparison of the Tenerife and COBE DMR data was made by Lineweaver *et al.* (1995) who demonstrated a clear correlation between the data sets at Dec.=+40° and showed the presence of common individual features. Bunn, Hoffman & Silk (1996) applied a Wiener filter to the two-year COBE DMR data assuming a CDM model. They obtained a weighted addition of the results at the two more sensitive frequencies (53 and 90 GHz) in the 7° beam COBE DMR data, and used the results of this filtering to compute the prediction for the Tenerife beam-switching experiments over the region 35° $\leq$Dec.$\leq$ 45°. At high Galactic latitude the most significant features predicted for the Tenerife data are two hot spots with peak amplitudes $\sim$ 50-100 μK around Dec.=+35° at RA$\sim$ 220° and $\sim$ 250°. Figure 4 compares the Bunn *et al.* (1996) prediction with the maximum entropy reconstruction (Jones *et al.* 1997) of our 15-GHz data reconvolved to be consistent with our beam geometry. The solid line shows the reconvolved results at 15 GHz after subtraction of the known point-source contribution as described in Section 3.1. The two most intense structures in these data agree in amplitude and position with the predictions from 53 and 90 GHz (dashed line), with only a slight shift in position for the feature at RA=250°. A possible uncertainty by a factor as large as 2 in the contribution of the point source 1611+34 would change the shape and amplitude of this second feature only slightly. In the range RA=160°-200°, there are more structure in the Tenerife reconstruction as compared with the predictions from the COBE DMR data. In that region, the Tenerife data are less sensitive as compared with the observations at higher RA, and therefore the maximum entropy reconstruction is less reliable. Other possible reasons for the discrepancy between both data-sets in that region, could be due to differences between the methods used in the reconstruction, or to galactic contamination in any of the data-sets.

The cross-correlation between the reconvolved data at 15 GHz and the predictions from the COBE DMR data have been plotted as a solid line in Fig. 2. The agreement between this cross-correlation and the autocorrelation amplitudes for our 15-GHz data reinforces the conclusion that most of the signal present in our 15-GHz data corresponds to intrinsic CMB structure.

4. CONCLUSIONS

We have presented new results from the Tenerife CMB experiments at 10 and 15 GHz. The sensitivity of the data at 15 GHz allows the detection of new individual hot and cold CMB spots. The data at 10 GHz are noisier but sensitive enough to show evidence of CMB signals, and to put constraints on the Galactic

contamination in the data at the higher frequency. A full joint analysis with our previous published results at 15 GHz in the largely independent strip at Dec.=+40° shows the statistical consistency between the results in both scans and puts limits on the expected quadrupole $Q_{\rm RMS-PS} = 21.0^{+6.5}_{-5.5}$ μK in the case of an standard inflationary scenario (i.e., a Harrison-Zeldovich spectrum). A comparison between our results and the COBE DMR predictions of Bunn *et al.* for our experiment assuming a standard CDM model shows a clear correlation between both, and the presence of strong common features in the region RA=$190° - 250°$. In forthcoming papers we will present in detail a separation between the CMB and the diffuse foregrounds and will make a rigorous comparison between the Tenerife and the four-year COBE DMR data including a joint likelihood analysis and a direct comparison of features.

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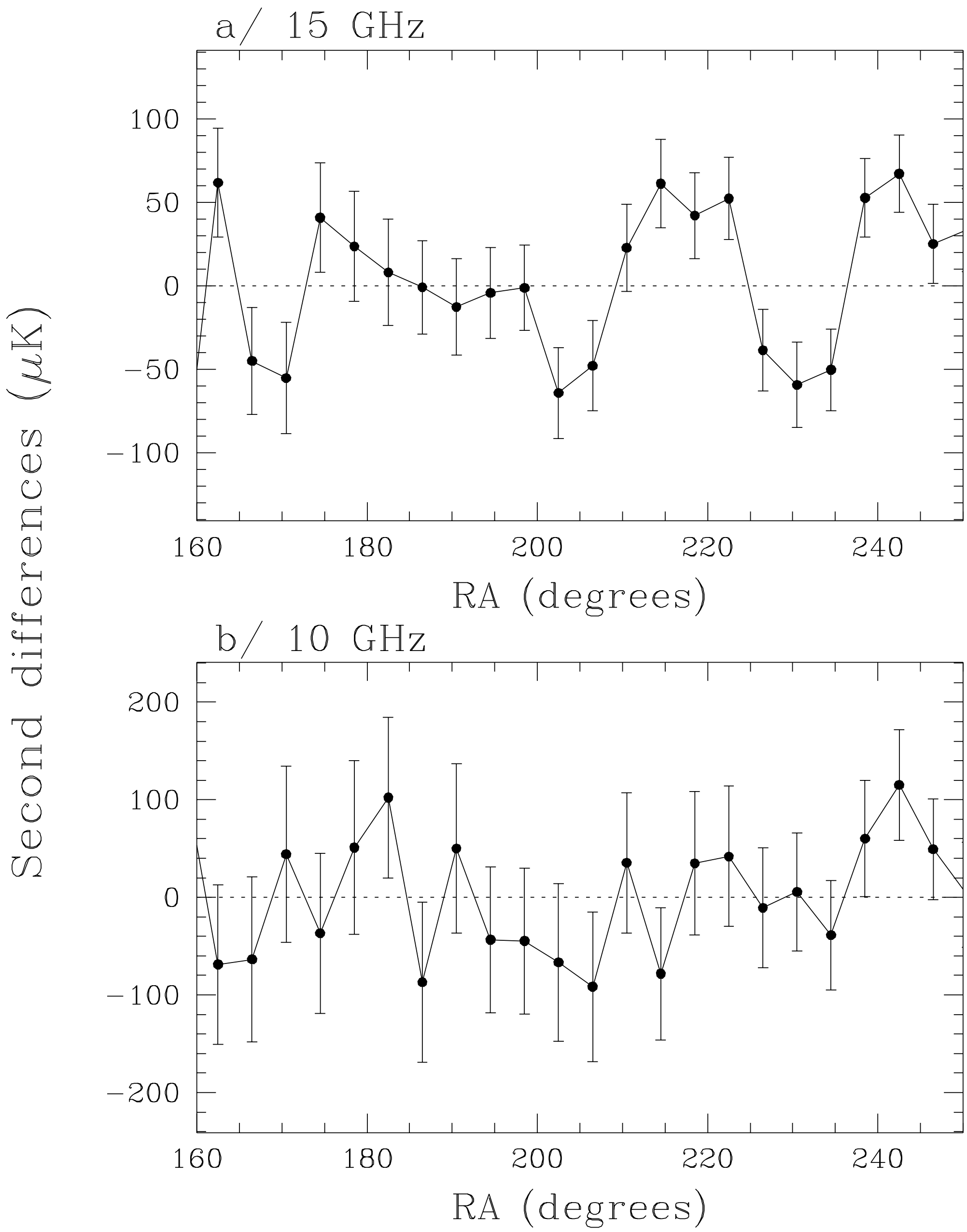
FIGURE CAPTIONS

Fig. 1.— The 10 and 15-GHz stacked scans at Dec=+35° in the region at high Galactic latitude between RA=160° and 250°. The data have been binned in 4° bins in RA. The lower noise ($\sim 20\ \mu$K) at 15 GHz allows the direct detection of structure at this frequency.

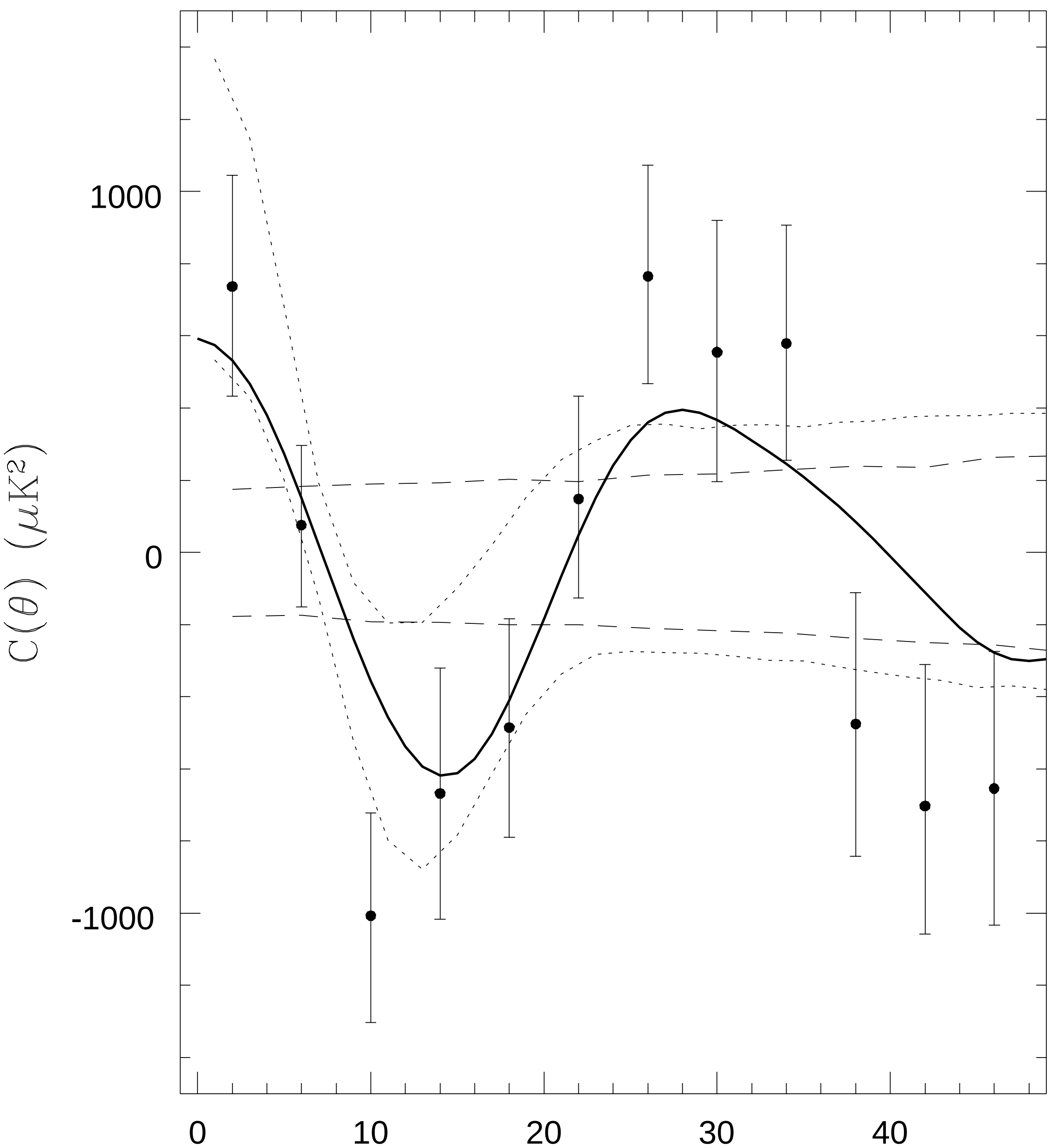
Fig. 2.— The auto-correlation $C(\theta)$ for the 15-GHz data, showing data points and one-sigma error-bars. The short dashed lines correspond to the uncertainties due to cosmic and sample variances for a Harrison-Zeldovich spectrum with $Q_{\rm RMS-PS} = 20.1\ \mu$K. The long-dashed lines enclose the expected 95% confidence limits bands for the correlation in the case of pure uncorrelated noise. The solid line is the cross-correlation between the reconvolved results at 15 GHz and the predictions from the COBE DMR data from Bunn *et al.* (1996-see main text for the details). The good agreement between the correlation plots confirms the CMB origin of structure in the frequency range 15 to 90 GHz.

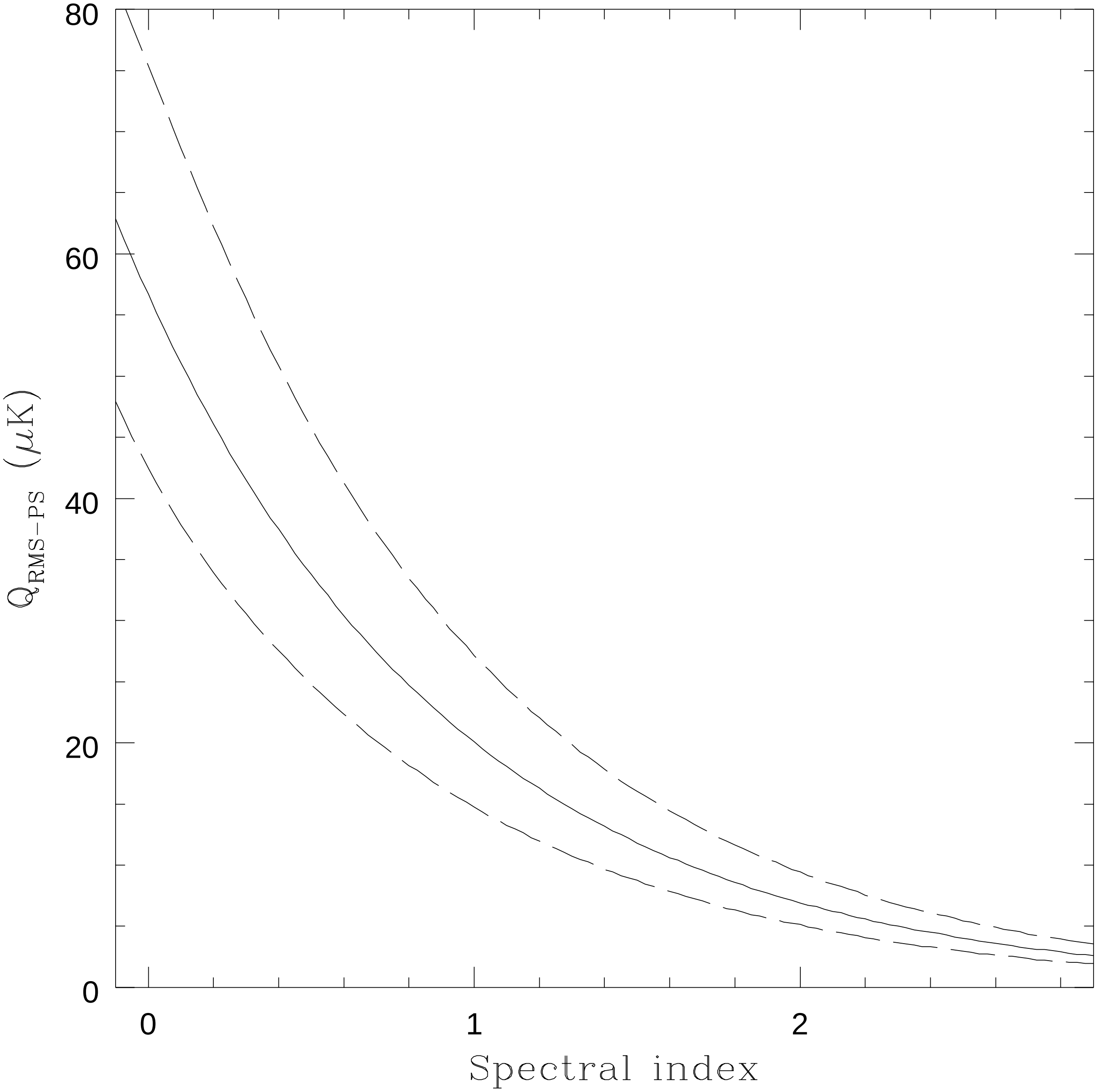
Fig. 3.— Constraints on the quadrupole $Q_{\rm RMS-PS}$ and on the spectral index n of fluctuations obtained from a joint-likelihood analysis of our data at Decs.=+35° and +40° at 15 GHz. The dashed curves show the one-sigma uncertainties. The plots indicate that for the Harrison-Zeldovich spectrum ($n = 1$) $Q_{\rm RMS-PS} = 21.0^{+6.5}_{-5.5}\ \mu$K.

Fig. 4.— Comparison between the maximum entropy reconstruction of the Tenerife Dec.=+35° data at 15 GHz (solid line) and the COBE DMR predictions of Bunn *et al.* (1996) (dashed line) at 53 and 90 GHz.

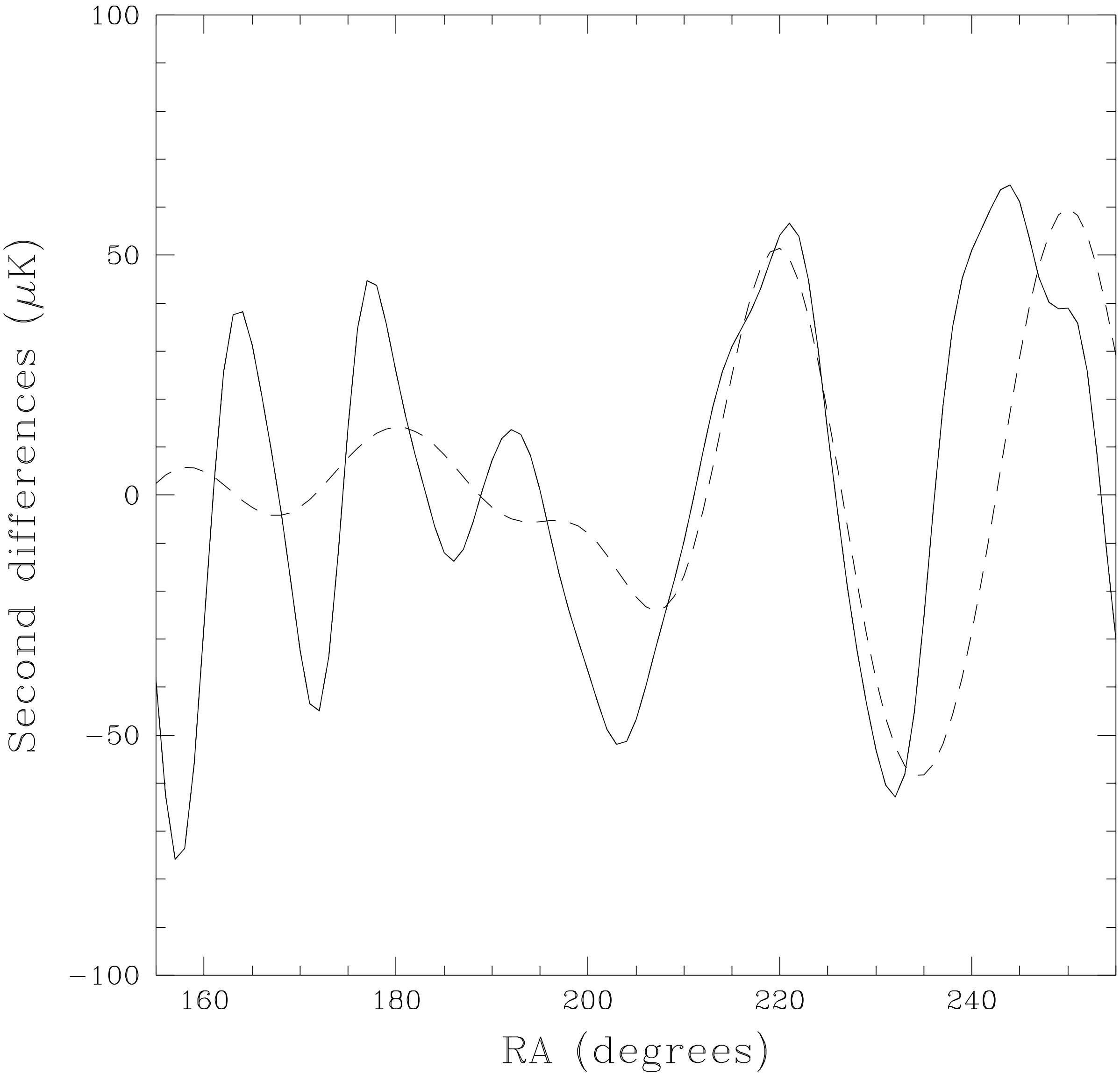


a/ 15 GHz
100
50
0
−50
−100
160
180
200
220
240
RA (degrees)
b/ 10 GHz
200
100
0
−100
−200
160
180
200
220
240
RA (degrees)
Second differences (μK)


1000
0
-1000
0
10
20
30
40
C(θ) (μK²)
θ (degrees)



80
60
40
20
0
0
1
2
$Q_{\mathrm{RMS-PS}}$ (μK)
Spectral index


100
50
0
−50
−100
160
180
200
220
240
Second differences (μK)
RA (degrees)